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Design and Manufacture of a Propellant Tank Assembly

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DESIGN AND MANUFACTURE OF A PROPELLANT TANK ASSEMBLY

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ABSTRACT

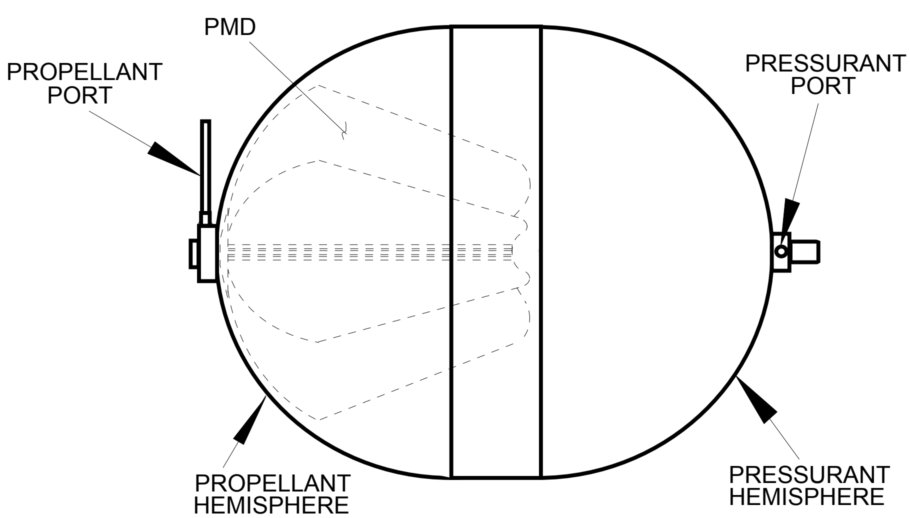
A propellant tank assembly is required for a spacecraft application. This tank must provide gas-free expulsion of propellant in a low gravity environment. An internally mounted surface tension propellant management device (PMD) is utilized to achieve this goal. The PMD is a vane type device constructed of titanium. An extensive development program was performed to determine the PMD characteristics. The development program included two vibration tests, two stiffness tests, and a slosh test.

The propellant tank shell is constructed of 6AL-4V titanium alloy. This material provides excellent strength to weight characteristics and is widely used in the aerospace industry for its manufacturability. A titanium forging qualification program was conducted to validate the forging design; and a complete qualification program was conducted to verify the tank design, including a final destructive burst pressure test. The tank qualification program was successfully completed on 17 February 1997.

INTRODUCTION

A propellant tank assembly is designed to provide hydrazine fuel for spacecraft thrusters. This pressure vessel utilizes a surface tension propellant management device (PMD) to provide gas-free expulsion of propellant upon demand in a low gravity environment. The PMD structure also controls the propellant center-of-mass during spacecraft maneuvers[1]. A sketch of this tank is shown in Figure 1.

Figure 1: Propellant Tank Assembly



The tank is mounted to the spacecraft by the two polar bosses. The propellant boss has four threaded holes for attachment of a U-joint assembly to the tank. This U-joint assembly provides mounting of the tank to the spacecraft structure. The pressurant boss mounts on a slip joint bearing which is designed to accommodate the tank's axial growth during pressurization. These mounting features are designed to minimize membrane weight by keeping all spacecraft induced loads out of the tank shell.

The propellant tank was designed to the following requirements:

Table 1: Propellant Tank Assembly Design Requirements

Parameters	Requirements
Operating Pressure	<1 torr to 400 psia @ 104 °F
Proof Pressure	600 psig @ 104 °F
Burst Pressure	800 psig minimum @ 104 °F
Expulsion Efficiency	99%
Propellant Weight	225 lbm Hydrazine
Tank Capacity	7700 in^3 minimum
Size	22.21" OD x 29.47" long
Tank Weight	20 lbm maximum
Fluid	Hydrazine
Shell Leakage	$<1x10^{-6}$ std cc/sec He @ 400 psig
On-Orbit Temperatures	54 °F to 104 °F

DESIGN ANALYSES

The tank design analyses included stress analysis and fracture mechanic analysis for the tank shell, and stress analysis for the PMD. Since the PMD is completely enclosed within the tank shell, a fracture mechanics analysis is not required for the PMD.

Tank Shell Stress Analysis: A stress analysis was performed to design the tank shell. The analysis took into consideration the design requirements such as:

- Temperature environment;
- Material properties;
- Mass properties of tank shell material;
- Mass properties of fluid;
- Fluids used by the tank;
- Tank pressurization history;
- External loads;
- Girth weld offset and weld suck-in;
- Design safety factors;
- Tank boundary conditions;
- Size of girth weld bead;
- Residual stress in girth weld; and
- Load reaction points.

The stress analysis concluded with positive margins of safety for all design parameters, as summarized below:

Table 2: Propellant Tank Safety Margins

Characteristics	M.S.
Burst pressure, sphere	+0.060
Burst pressure, cylinder	+0.004
Burst pressure, heat affected zone	+0.100
Burst pressure, weld	+0.0
Burst pressure, hemi/cylinder transition	+0.016
Burst pressure, pressurant boss	+0.025
Burst pressure, propellant boss	+0.030
Proof pressure, membrane, sphere	+0.290
Proof pressure, membrane, cylinder	+0.200
Proof pressure, heat affected zone	+0.320
Proof pressure, weld	+0.140
Proof pressure, hemi/cylinder transition	+0.100
Proof pressure, pressurant boss	+0.200
Proof pressure, propellant boss	+0.220
External pressure, sphere	+0.007
External pressure, cylinder	+0.210

Tank Shell Fracture Mechanics Analysis: A fracture mechanics analysis was performed to establish whether the growth of an initial flaw in the anticipated cyclic and sustained pressure environment may cause a failure in the tank shell. The analysis was performed using external and internal stresses from the stress analysis, and using NASA/FLAGRO with minimum thicknesses as parameters. A special fracture critical dye-penetrant method is required to detect flaws. The minimum flaw sizes that can be detected by such special dye penetrant inspection were used as initial flaw size for this fracture mechanics crack propagation analysis. The analysis was performed at:

- Girth welds and heat affected zones;
- Maximum pressure stress location in the hemisphere;
- Maximum stress location in the cylinder;
- Maximum stress location in the hemisphere/cylinder transition;
- Intersection between the hemisphere and the pressurant boss;
- Intersection between the hemisphere and the propellant boss;
- Maximum external load stress in the hemisphere near the pressurant and the propellant bosses;
- PMD attachment;
- Discontinuity in the tank shell at the perforated plate shelf.

The tank was designed to meet all the fracture mechanics requirements.

PMD Stress Analysis: A PMD stress analysis was also performed to validate the PMD design. The analysis took into consideration design requirements such as material properties, flight loads, design safety factors, and residual stress in weld. The stress analysis concluded with positive margins of safety for all design parameters, as summarized below:

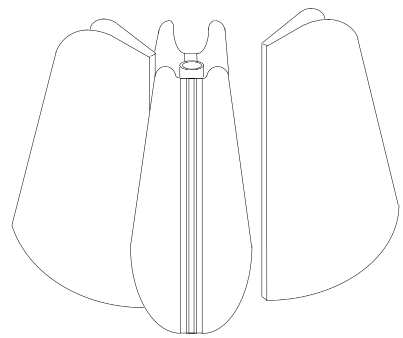
Table 3: PMD Safety Margins

Characteristics	M.S.
PMD vanes, yield	+0.43
PMD centerpost, yield	+3.93
PMD shaft, yield	+0.48

PMD DESIGN AND FABRICATION

A vane-type design is being used for the PMD. The design and functionality of this PMD is detailed in a technical publication[1]. This PMD assembly consists of a centerpost and four (4) identical vane assemblies each containing two (2) identical vanes. See Figure 2. The vane assemblies are welded to the center post to form the PMD assembly. The eight (8) vanes in the PMD assembly are equally spaced and each vane is oriented 45 degrees from the adjacent vanes. The PMD centerpost is machined from 6AL-4V titanium bar. The PMD vanes are cut from 0.012 inch thick 6AL-4V Titanium sheet stock.

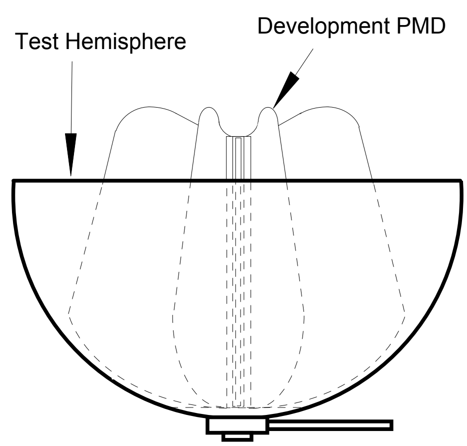
Figure 2: The PMD Assembly



PMD DEVELOPMENT

An extensive development program was commissioned to determine the characteristics and to verify the structural integrity of the PMD. A complete PMD, as well as a test propellant hemisphere, were fabricated for this development program. Both the PMD and the test hemisphere were processed the same as the flight hardware and assembled with production tooling. This PMD development unit resembles the flight tank expulsion assembly, as shown in Figure 3.

Figure 3: PMD Development Unit



The PMD development test program was conducted in two phases, separated by a heat treat cycle.

Dry random vibration test, pre-heat treat: The development unit was subjected to the acceptance and qualification level random vibration spectrum for a period of 60 and 180 seconds, respectively. Three (3) axes were tested, including two (2) lateral and one (1) longitudinal axes. Accelerometers were used to control and monitor energy input and the test specimen response. The control accelerometer was installed on the baseplate near the outlet port. The response accelerometers were installed on the PMD centerpost, on the test fixture, and on the test fixture baseplate. Four (4) strain gauges were also installed on the PMD centerpost to monitor the strain levels of the PMD centerpost during test. A typical vibration test setup for a lateral axis test is shown in Figure 4.

The development unit was installed in the test fixture and restrained in such a way that the hemisphere remained rounded during the vibration test. The primary accept-reject criteria were:

(1) the PMD vanes must not come into contact with the hemisphere wall during vibration testing, and

(2) the gap between the PMD and the hemisphere wall must meet the drawing requirements after the vibration test.

Throughout all the test runs, the PMD vanes never contacted the hemisphere wall. Post test dimensional inspection also showed that the gap between the PMD and the tank wall did not change significantly after the test.

Stiffness test, pre-heat treat: The stiffness test was designed to determine the deflection versus load characteristics of the PMD. This test applied a force on top of the PMD center post to produce a lateral deflection, and the resultant PMD displacement and strains were measured and recorded. The test was conducted twice: once with the lateral force exerted between the vanes, and once with the lateral fore exerted in line with the vanes. The force was applied in 20 lb_f increments from 0 to 100 lb_f. Figure 5 shows the test setup for the stiffness test.

The test specimen remained installed in the vibration test fixture to insure the roundness of the hemisphere during test. The same strain gauges used in the vibration test were utilized to monitor the strain level of the PMD centerpost. PMD displacement was measured by Linear Velocity Displacement Transducer (LVDT) units located on the PMD vanes. Acceptance criteria was that the PMD vanes must not touch the hemisphere wall and the perforated sheet throughout the test.

The test results showed that the 100 lb_f lateral force produced a maximum lateral deflection of 0.123”. The gap between the PMD vane and the hemisphere wall was narrowed by 27%, and the gap between the vane and the perforated sheet was narrowed by 42%. Both conditions were within tolerance limits.

The PMD designers were particularly concerned about the strain levels at the PMD center post during the test, and a plot of force vs. strain was produced to examine the strains, as presented in Figure 6. All strains were found to be within acceptable limits.

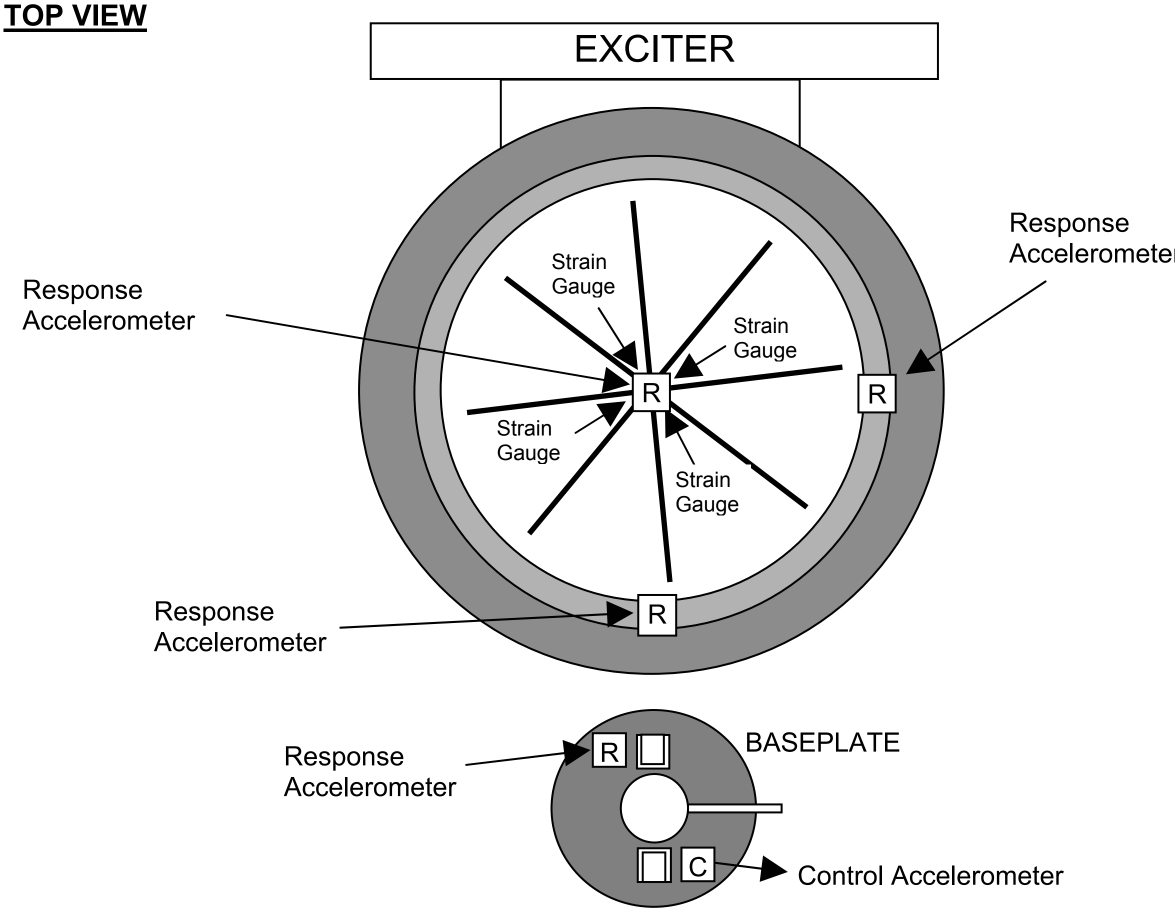
Heat treat:. Following the stiffness test, the test specimen was heat treated to simulate the tank post girth weld stress relief cycle and final age. The strain gauges were removed prior to heat treat to prevent material contamination, and were not re-installed for the subsequent development tests.

Stiffness test, post-heat treat: Following the heat treat cycle, another stiffness test was conducted using the same LVDT units as in the previous stiffness test. Test results showed that the 100 lb_f produced a maximum lateral deflection of 0.178”. The vane-to-hemisphere wall gap narrowed by 38%, and the vane-to-perforated sheet gap narrowed by 62%. The test results clearly showed that the PMD stiffness was reduced after heat treat, but the reduction was not significant enough to affect the performance of the PMD.

Dry random vibration test, post-heat treat: After the stiffness test, the development unit was subjected to the same vibration test described previously, at both acceptance and qualification levels. Post test inspection showed that the development unit met all the specification requirements. This test proved that the post girth weld heat treat would not significantly affect the PMD functionality.

Figure 4: Vibration Test Setup

TOP VIEW



SIDE VIEW

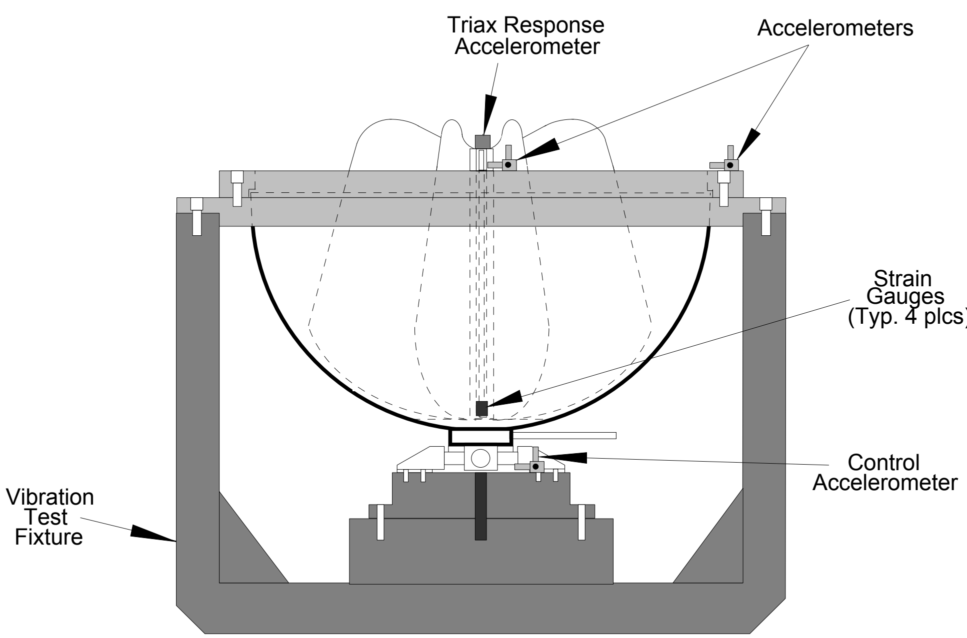
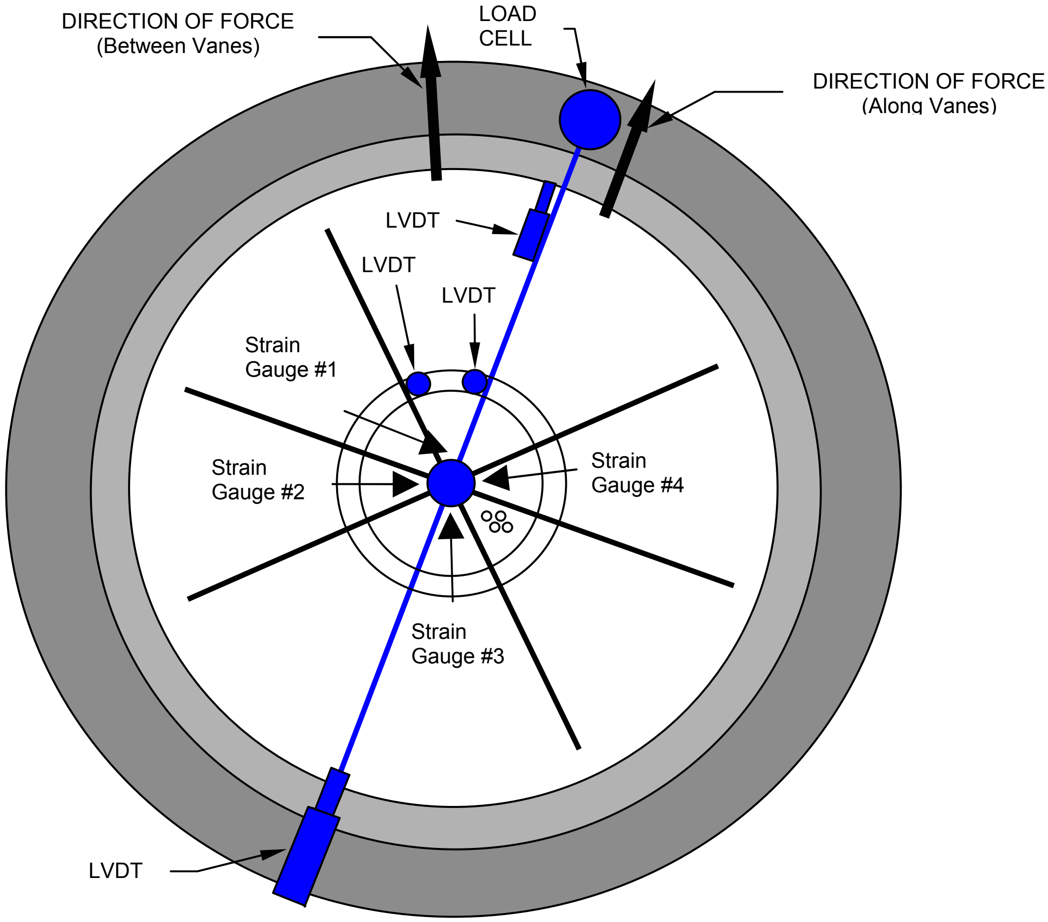


Figure 5: Stiffness Test Setup

TOP VIEW



SIDE VIEW
(rotated for clarity)

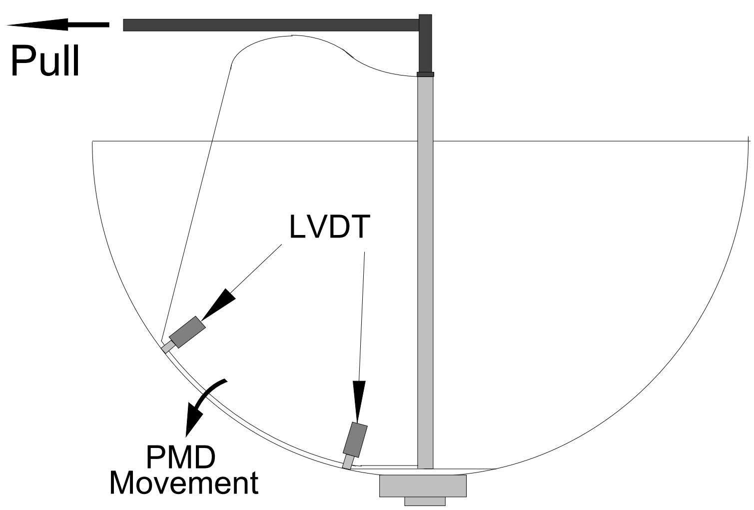
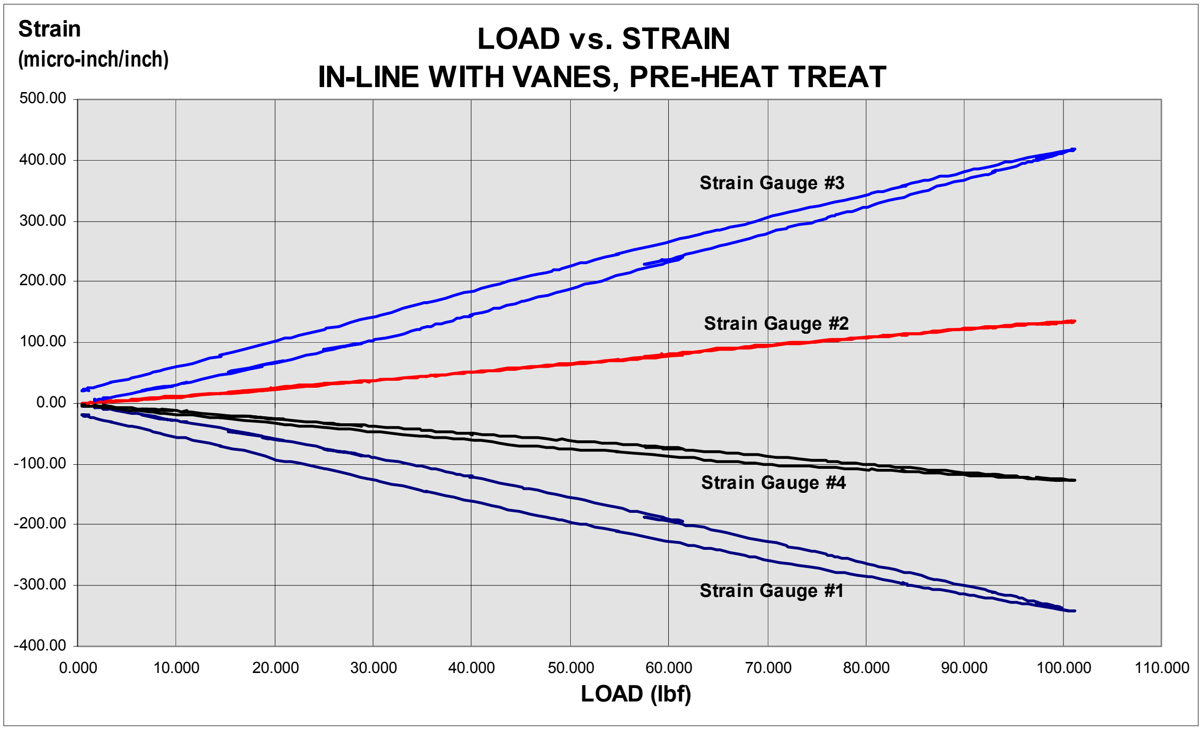


Figure 6: Stiffness Test Results



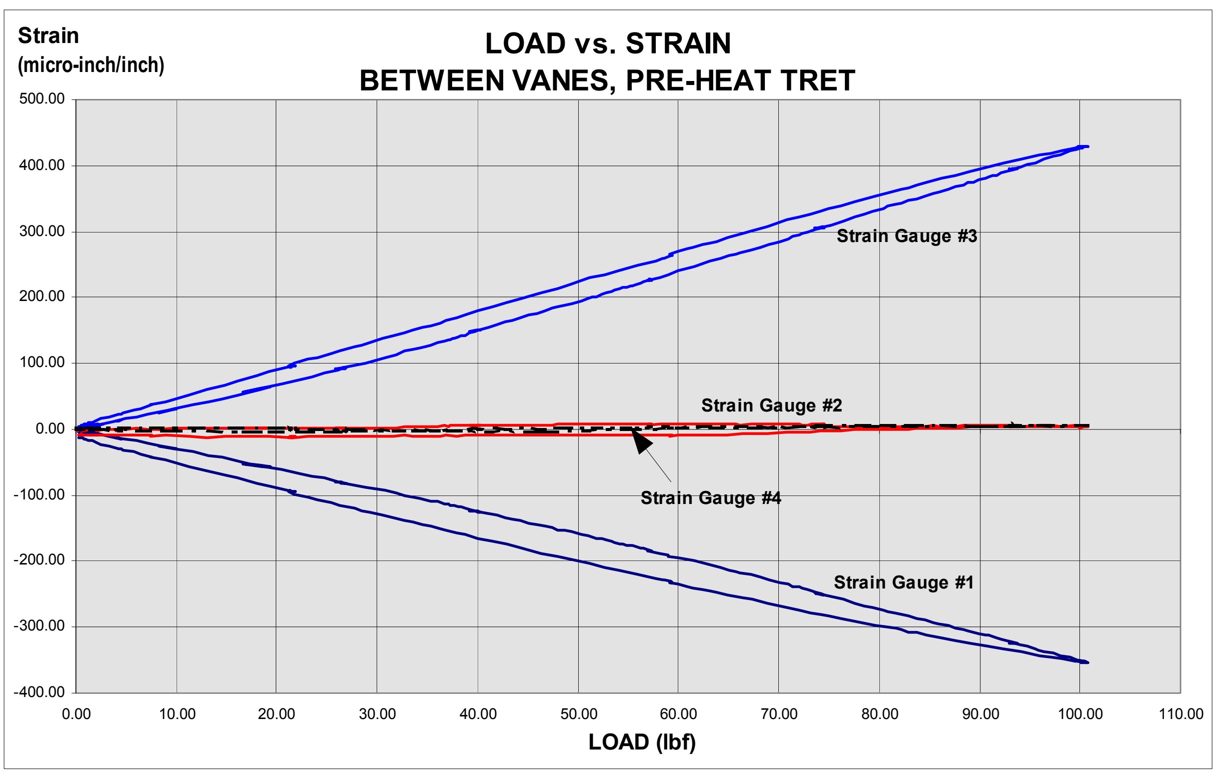
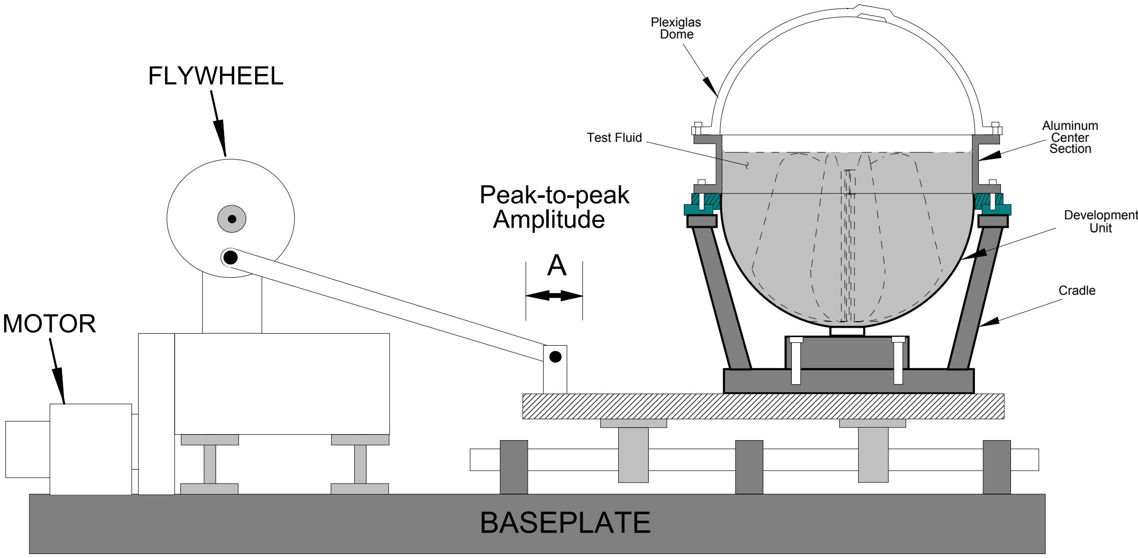


Figure 7: Slosh Test Setup



Slosh test: A slosh test was performed on the test specimen following the random vibration test. The test setup is shown in Figure 7. An aluminum ring was used to simulate the tank center section, and a 2" thick transparent Plexiglas dome was used to simulate the pressurant hemisphere. The Plexiglas dome allowed visual observation of the PMD and the fluid motion during the slosh test.

The entire assembly was mounted on top of the slosh test fixture as shown in Figure 7. This test fixture was configured to produce two lateral, sinusoidal inputs: (1) **A** = 1.7 inch peak-to-peak stroke, and (2) **A** = 3.4 inch peak-to-peak stroke. All slosh testing was performed over these two input levels.

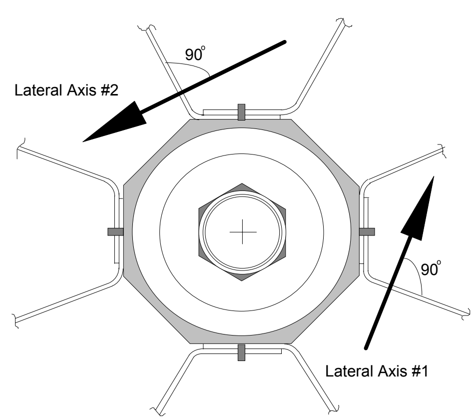
Deionized (D.I.) water was used as test fluid. To find the worst case fill level and the resonant frequency, the test was conducted at various fill levels:

- At 1 inch below the top of the vanes;
- At the top of the vanes;
- At the top of the center section;
- At maximum fill fraction (≈225 lbm water).

At each fill level, testing was conducted over the frequency range from 0.8 Hz (48 cycles per minute) to 2.8 Hz (168 cpm) at either 1.7 inch or 3.4 inch amplitude in increments sufficiently small to determine the worst case slosh. The worst case slosh condition occurred when the fluid level was about 1" below the top of the vanes. Both the acceptance and qualification level tests were conducted at this fill level. When the tank was filled to the top of the vanes, sloshing became less severe. At an even higher fill level, when the fluid is several inches above the top of the vanes, the fluid developed a swirling motion during cycling.

The two slosh axes are shown in Figure 8 below:

Figure 8: Slosh Axes



For both Lateral #1 and Lateral #2 axes, and at both 1.7 inch and 3.4 inch input strokes, the resonant frequency remained consistently between 72 and 74 cycles per minute throughout all slosh testing.

The acceptance tests for the two test axes were conducted with the tank filled with 160 lbm of water, at the input stroke of 1.7 inches and at a frequency of 1.2 Hz, for a duration of 38 minutes. The qualification tests for the two test axes were conducted with the tank filled with 160 lbm of water, at the input stroke of 3.4 inches and at a frequency of 1.2 Hz, for a duration of 114 minutes.

Final Inspection: The development unit successfully passed all the development tests without any physical degradation, and met all the dimensional requirements. The PMD welds were further subjected to both radiography and penetrant inspection and no weld cracks were detected.

FORGING QUALIFICATION

A forging qualification program was conducted to validate the hemispherical forging manufacturing method and the forging die. The heat treatment temperature determination for the forgings was also an integral part of this process and was conducted concurrently with the forging qualification program. A forging was randomly chosen from the manufactured lot and subjected to the following process sequence, including destructive testing, to qualify all forgings manufactured from the forging die:

- Micro structure examination;
- Rough machining;
- Ultrasonic inspection;
- Solution heat treat and quench;
- Saw cut samples;
- Heat treat temperature determination;
- Heat treat samples;
- Chemical content (Hydrogen, Oxygen, and Nitrogen);
- Tensile test for mechanical properties;
- Micro structure examination;
- Grain flow examination.

The as-forged micro specimen, collected prior to forging processing, was mounted, polished, and evaluated for grain size. Following micro specimen collection, the forging was rough machined to reduce the hemisphere wall to a thickness in which the effect of heat treatment can be maximized.

After solution heat treat and age, sample coupons were cut from various regions of the forging including boss, membrane, weld, and prolongation. Several trial heat treats were conducted on coupons to determine the optimum heat treatment that produces the best mechanical properties. Following heat treat determination, all remaining sample coupons were heat treated at this pre-determined temperature. Some heat treated samples were subjected to chemical analysis and tensile tests to determine their chemical content and mechanical properties, other samples were subjected to micro structure and grain flow examinations for evaluation of their metallic structure.

PROPELLANT TANK ASSEMBLY FABRICATION

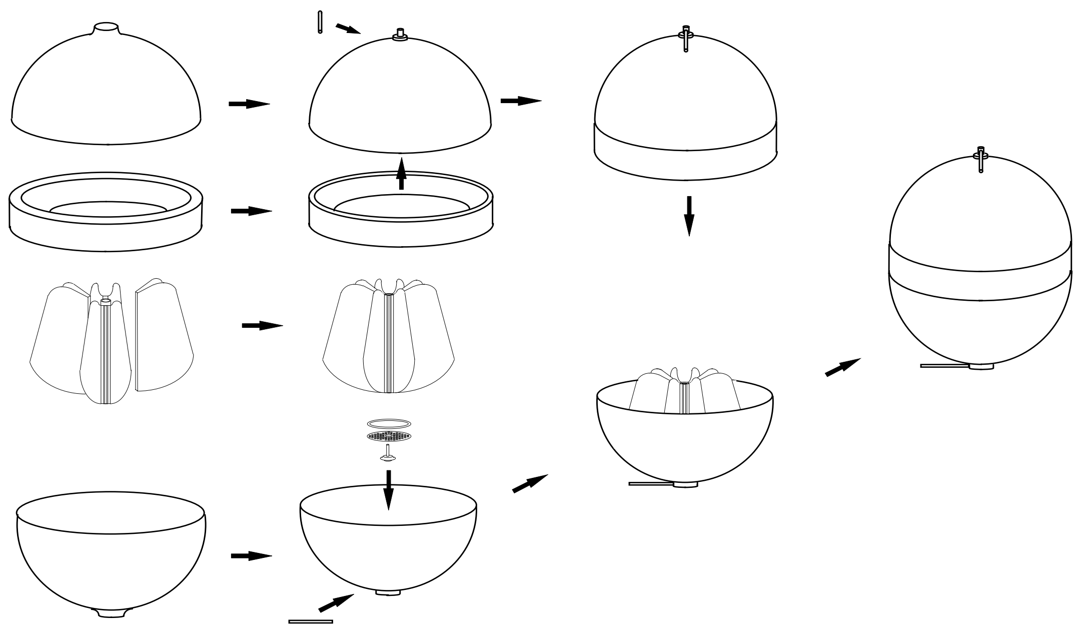
Figure 9 presents the manufacturing sequence of the propellant tank assembly.

The propellant tank shell consists of two hemispheres and one center section. Both the hemispheres and the center section ring are machined from 6AL-4V titanium alloy forgings. Each forging is rough machined, solution heat treated and quenched, partial aged, skim machined and finish machined. The as-delivered hemispherical forgings have a nominal thickness of 0.56 inch, and the finished tank shell membrane has a nominal thickness of 0.032 inch. The entire machining process removes over 95% of the forging material.

After the completion of the tank shell, a PMD shaft and a perforated plate are welded to the propellant hemisphere to form the PMD base, and the inlet and outlet tubes are welded to the hemispheres. The assembled PMD is then installed onto the PMD shaft to complete the expulsion assembly. The expulsion assembly must be vibration tested and cleaned prior to tank closure.

Two girth welds are required to assemble the tank. The first weld joins the pressurant hemisphere and the center section. The second joins the hemisphere/center ring assembly to the expulsion assembly to complete the tank closure. Both girth welds are subjected to fracture critical radiographic and dye penetrant inspection. After closure the tank assembly is stress relieved and final machined prior to acceptance testing.

Figure 9: Propellant Tank Assembly Manufacturing Flow



ACCEPTANCE TESTING

A very unique feature of this propellant tank is that a component level acceptance random vibration test is performed on the expulsion assembly prior to tank closure. The test is designed to validate the PMD workmanship. This random vibration test is conducted the same as the development unit vibration tests described previously, except that the expulsion assembly is only subjected to the acceptance level vibration spectrum for a duration of 60 seconds. The expulsion assembly must meet all dimensional requirements after the vibration test before proceeding to tank closure.

After the tank is assembled, it is subjected to the following acceptance tests prior to delivery:

- Preliminary examination
- Pre-proof volumetric capacity
- Ambient proof pressure
- Post-proof volumetric capacity
- Pressure drop test
- Negative pressure test
- External leakage test
- Penetrant inspection
- Radiographic inspection
- Final examination
- Cleanliness

Conservatism is exercised throughout the test program, and all pressure testing is temperature adjusted for the worst case operating temperature (104 °F).

Volumetric Capacity Examination: The capacity of the propellant tank is measured using the weight of water method, using clean, filtered deionized water as the test medium. This test is conducted before and after the proof pressure test to verify that the proof pressure test does not significantly alter the tank capacity. A successful validation indicates that the tank shell is manufactured properly and that the tank can operate in the pressure environment under which it was designed for. Typically, the volumetric growth after proof pressure test is zero.

The post-proof test capacity examination also serves to verify that the tank meets the designed volume requirement.

Proof Pressure Test: The proof pressure test is typically the first pressurization cycle applied to the tank after fabrication. It is intended to validate the workmanship by verifying the strength and integrity of the tank shell. The test must be conducted in a “safe” environment to minimize hazards to test technicians. The test is conducted hydrostatically at proof pressure

(600 psig, normalized for test temperature) for a pressure hold period of 5 minutes. The radial and longitudinal growths of the tank at proof pressure were measured using dial gauges. The propellant tank typically grows 0.060 inch radially and 0.027 inch longitudinally, but returns to its pre-pressurization configuration after the test.

Pressure Drop Test: The propellant tank must meet the pressure drop requirement of not-to-exceed 1.0 psid at a maximum flow rate of 0.01 lb/sec. The test is conducted by measuring the pressure differential between ullage and the tank outlet while pressuring the tank (and the test fluid) through the pressurant port. Typically, pressure drop through tanks is negligible; this is true for all the propellant tanks built to date.

Negative Pressure Test: The propellant tank shell must withstand a pressure differential of 16.2 psid across the tank membrane. This requirement is verified by acceptance test. To accomplish the 16.2 psid pressure differential, the test must be conducted in a pressure chamber where external pressure is applied on the tank shell while the tank is being evacuated. The 16.2 psid pressure differential must be maintained for 30 seconds minimum for the test.

External Leak Test: The external leak test verifies the integrity of the tank shell and also serves to validate the above pressure tests. The tank is placed in a vacuum chamber, which is evacuated to under 0.2 microns of mercury, and helium pressurized to 400 psig for 10 minutes. The helium leak rate cannot exceed 1×10^{-6} std cc per second after the 10-minute stabilization period.

Non-Destructive Examination: Following the pressure tests, the tank shell is screened for flaws using fracture critical penetrant inspection and fracture critical radiographic inspection techniques. Tank acceptance after NDE marks the successful completion of acceptance testing.

Cleanliness Verification: After the non-destructive examination, the interior of each flight tank is cleaned to the cleanliness level specified below in Table 4:

Table 4: Propellant Tank Cleanliness Level

Particle Size Range (Microns)	Maximum Allowed per 100 ml per ft^2
0 to 15	265
16 to 25	78
26 to 50	11
51 to 100	1
101 and over	0

QUALIFICATION TEST PROGRAM

Since this propellant tank is a new design, a tank qualification program is required. A designated qualification tank was fabricated for the Qualification Test Program. The qualification tank was constructed the same as the flight tanks, using the same processes, procedures, and tooling.

The Qualification Test Program consists of a series of tests intended to verify the tank design in the following areas:

- PMD workmanship
- Fatigue
- Tank shell integrity
- Burst margin

Pass/Fail criteria consists of acceptance type external leak tests and non-destructive evaluations conducted at intervals throughout the test program. After the tank passes the final external leak test, it must undergo a final burst pressure test. A successful burst certifies the tank for flight use.

Qualification Vibration Test: Unlike most other qualification programs where vibration tests were conducted on finished tanks, this program conducted qualification vibration test on the expulsion subassembly. This component level random vibration test was conducted the same as the development unit described previously, and the test duration was 60 seconds at the acceptance level and 180 seconds at the qualification level for each vibration axis.

Test Sequence: The Qualification Tank was subjected to the acceptance tests (except cleanliness) followed by these qualification tests:

- Pressure cycles
- Negative pressure cycle
- External leakage
- Centrifuge
- External leakage
- Penetrant inspection, tank shell
- Penetrant inspection, tube welds
- Radiographic inspection of all welds
- Final examination
- Destructive burst pressure

Pressure Cycles: A total of 60 pressure cycles from 30 to 464 psig and 15 proof cycles from 30 to 600 psig were conducted. Pressure hold period was 30 seconds minimum at each cycle.

Negative Pressure Cycles: The negative pressure cycle test was an extension of the pressure cycle test. The test setup was the same as the negative pressure test. The test consisted of one evacuation cycle from 0 to 18.4 psid and eleven evacuation cycles from 0 to 14.7 psid. Pressure hold period was 30 seconds minimum at each cycle.

Centrifuge Test: The centrifuge test simulated the "g" force exerted on the tank shell by the propellant during launch. The test was conducted with the tank loaded with 224 lbm of water and pressurized to 400 psig (adjusted for test temperature).

The Qualification tank was tested under two conditions: compression and tension. See Figure 10. In the compression test, the tank was mounted at a 41° angle and leaned toward the axis of rotation. This configuration exerted a 14.5 g force on the tank shell at 56 revolutions per minute (rpm) during test. For the tension test, the tank was mounted at a 60° angle and leaned away from the axis of rotation. This configuration exerted a 9.5 g force on the tank shell at 41 rpm. For both configurations, the test duration was one minute at steady state.

Test instrumentation included twenty (24) strain gauges, 12 near the propellant boss and 12 near the pressurant boss; and an accelerometer located at the center of the tank. The strain levels at both ports were monitored throughout the test by the strain gauges, including before and during pressurization, spin up, actual test run, spin down, and de-pressurization. Test results showed maximum strain level near 900 microstrains. The accelerometer was installed to validate the test result and also to prevent any over- or under-test.

Destructive Burst: After the completion of the qualification tests, the Qualification Tank was subjected to a final destructive burst pressure test. The tank burst at 1113 psig, or 35% above the design burst requirement.

Figure 11 presents a photograph of the tank after burst. It is a textbook example of a tank burst, with the fracture initiated at the reinforcement-to-membrane transition region and away from the girth welds. The PMD was not damaged by the tank shell fracture.

Qualification Tank Pressure Log: In summary, the Qualification Tank has undergone the following pressure cycles:

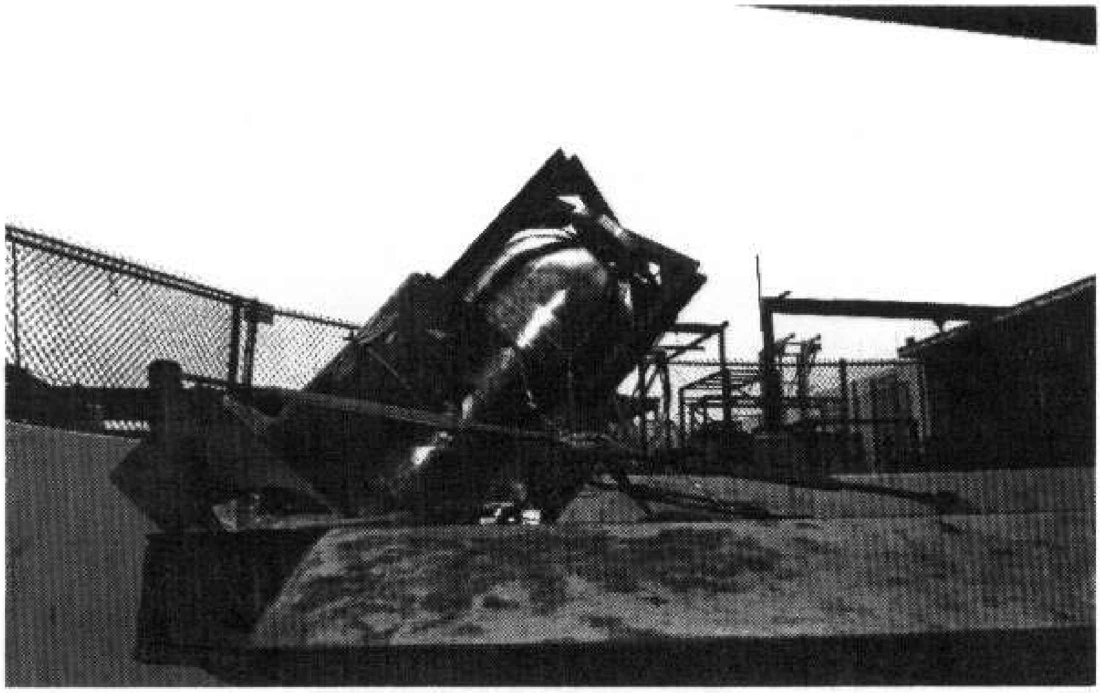
Table 5: Summary of Qualification Tank Pressure Cycles

Pressure	No. Cycles	Description
600 psig* Proof pressure	16	1 proof test, 15 proof cycles
464 psig* operating pressure	60	Pressure cycle test
400 psig* operating pressure	5	3 external leak tests 2 centrifuge tests
100 psig	1	Pressure drop test
-18.4 psid	1	Negative pressure cycle test
-16.2 psid	1	Negative pressure
-14.7 psid	11	Negative pressure cycle test

*Test pressure adjusted for test temperature

Figure 10: Centrifuge Test Setup

COMPRESSION



TENSION

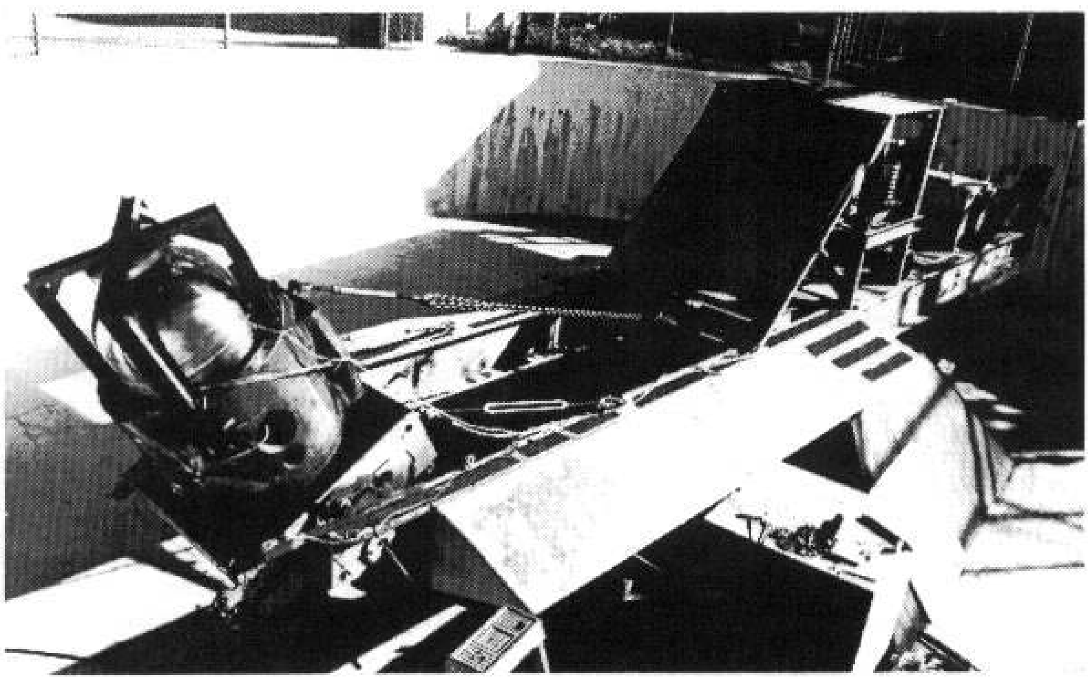
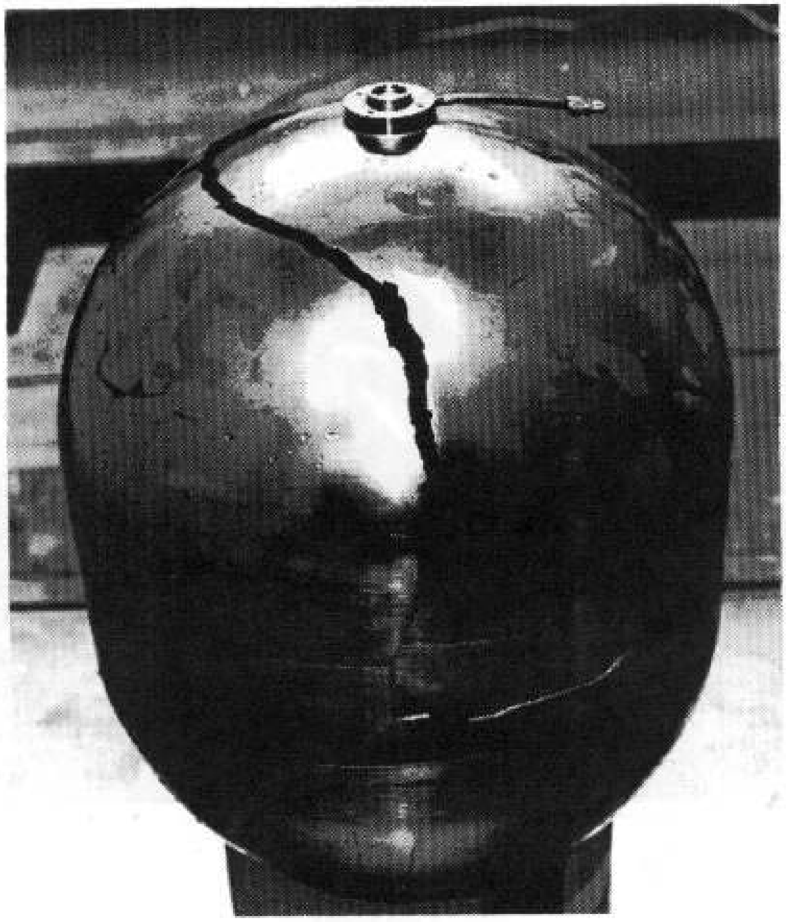


Figure 11: Propellant Tank After Burst



WEIGHT DISTRIBUTION

The propellant tank weight distribution is summarized in the table below:

Table 6: Propellant Tank Weight Distribution

Item	Nominal Weight (lbm)
Tank Shell	16.15
PMD Mounting Shaft	0.35
PMD	3.50
TOTAL	**20.00**

The Qualification tank weighs 19.92 pounds.

CONCLUSION

The propellant tank assembly has successfully concluded qualification testing without failure. The production program is complete and all flight tanks have been delivered.

The PMD has a simple, robust design and is easy to manufacture. It has been extensively tested and shows excellent strength and durability.

The propellant tank assembly is light weight, high performance, and easy to manufacture. The tank assembly is accomplished using standard manufacturing processes and procedures. Special materials and processes are not required.

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REFERENCE

1. J. Tegart, A Vane-Type Propellant Management Device, AIAA 97-3028.

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